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**FRICTION AND WEAR BEHAVIOR OF ALUMINUM
AND COMPOSITE I-BEAM STIFFENED AIRPLANE SKINS**

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FRICTION AND WEAR BEHAVIOR OF ALUMINUM AND COMPOSITE I-BEAM STIFFENED AIRPLANE SKINS

by Karen E. Jackson

SUMMARY

Experiments were performed to compare the friction and wear behavior of aluminum and composite materials under conditions similar to the loadings experienced by skin panels on the underside of a transport airplane during an emergency belly landing. The test specimens consisted of I-beams with attached skins constructed of aluminum, graphite-epoxy, and glass hybrid. An abrasion test apparatus was designed and fabricated to perform wear and friction tests on the skin-stiffener elements. The specimens were abraded on actual runway surface under a range of pressures (2-5 psi) and velocities (16-50 mph). These parameters were chosen to fall within the range of conditions considered typical of an emergency situation in which an airframe would be sliding on a runway surface. The test apparatus was equipped with instrumentation to measure the frictional forces developed during abrasion and monitor temperatures on the backside of the skin specimens.

The effects of the test variables (pressure and velocity) on the coefficient of dynamic friction, wear rate, and wear index were determined and comparisons made between the composite materials and aluminum. Wear rate is defined as loss of skin thickness per unit of run time and wear index is a nondimensional wear parameter obtained by normalizing the wear rate by the test velocity. The composite materials exhibited wear rates 2 to 3 times higher than the aluminum, with little variation between the glass hybrid composites and the graphite-epoxy. The wear behavior was generally a linear function of pressure and velocity. The coefficient of dynamic friction for the composite materials was approximately half that of the aluminum and, for both material types, appeared to be a linear function of the test variables. Results of the temperature data indicated that the temperature on the backside of the composite specimens remained fairly constant at the ambient level throughout abrasion. However, the aluminum specimens exhibited a high rate of increase in temperature over the 6 second run time.

INTRODUCTION

Composite materials are finding widespread application in the aircraft industry due to their excellent mechanical properties, tailorability, and light weight. The incorporation of composites in the design of future aircraft will make these aircraft more fuel-efficient, capable of increased pay-loads, and simplify the construction process by a reduced part count. In addition, utilization of energy absorbing composite structures in the design of the airframe may lead to safer, more crashworthy aircraft.

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An important consideration in the design of crashworthy transport aircraft is the friction and wear behavior of the skin material. In the last 5 years at least a dozen transport airplanes have experienced failure of the landing gear leading to sliding belly landings on runway surfaces (ref. 1). Typically, these transport airplane slide 4000 to 5000 ft with touchdown velocities of approximately 140 mph. Wear damage to the aluminum skin is considerable in some sections of the aircraft, but it is usually repairable. The trend in the aircraft industry towards increased use of composite materials in the construction of transport aircraft raises the question of how airplanes with composite skins would behave under these circumstances as compared with current aluminum skin construction.

This paper describes the second phase of an investigation to compare the friction and wear behavior of composite materials and aluminum under abrasive loading conditions similar to those experienced on the underside of a transport airplane during an emergency belly landing. In the first phase (ref. 2) small coupon skin specimens were abraded in the laboratory under a range of pressures and velocities in a test apparatus which utilized a belt sander to provide the sliding surface. The second phase, as described in this paper, involved abrading larger specimens consisting of I-beams with attached skins under similar conditions of pressure and velocity on actual runway surface. A test apparatus was designed and mounted on a flatbed trailer which was hitched to a second vehicle and hauled across the runway. The test apparatus was equipped with a hydraulic control system to raise and lower the I-beam test specimens to the runway surface and was instrumented to measure the frictional forces developed during abrasion. In addition, temperature measurements were monitored from thermocouples attached to the backside of the skins of the I-beam test specimens.

The skins attached to the I-beam test specimens were constructed of aluminum, graphite-epoxy, and two glass hybrid composite materials. The effect of the test variables (pressure and velocity) on the wear rate and coefficient of dynamic friction are discussed and comparisons are made between the composite material systems and the aluminum. Results of the temperature-time histories obtained during abrasion are also reported.

TEST APPARATUS AND PROCEDURES

Equipment

Apparatus.— The apparatus used to perform abrasion tests on the I-beam stiffened skins is shown in figures 1 and 2. The Integrated Tire Test Vehicle (ITTV) was used to haul the runway abrasion test trailer with the test apparatus mounted to it (fig. 1). All abrasion tests were performed on the Langley Air Force Base north-south ramp. This runway surface has a measured surface texture depth of 0.011 inches which is typical of heavily textured concretes and the majority of harsher types of asphalt (ref. 3). Figure 2 depicts a detailed view of the runway abrasion test trailer and apparatus. The I-beam test specimens were held in place by securing the top

flange to a specimen holder. The holder was attached to a parallelogram arrangement of mechanical linkages consisting of a large top beam, a rigid central support, a lower linkage arm, and the specimen holder. These four members were connected by pinned joints such that the specimen holder could be raised and lowered to the runway surface by pivoting the top beam. The specimen holder remained perpendicular to the runway surface because of the parallelogram linkage arrangement. As the skin of the I-beam specimen wore, the arrangement ensured that the load remained normal to the abrading surface. Loads were applied to the specimen by placing lead weights on the specimen holder as shown in figure 2.

Hydraulic System.- A hydraulic system was mounted to the trailer to control the action of the mechanical linkages in lowering and raising the test specimens to the runway surface. The system consisted of a pump, accumulator, 4-way valve, and a hydraulic cylinder. To lower the test specimen, the hydraulic system was actuated such that the hydraulic cylinder extended, thereby releasing the cable attached to the top beam of the linkage assembly. The system worked in reverse to raise the test specimen. The location of the hydraulic equipment on the trailer is shown in figure 2.

Control System.- Operation of the abrasion tests was automated through a control circuit located in a box shown in figure 2. The control circuit, once initiated by an operator in the ITTV cab, time sequenced the hydraulic system which lowered the test specimen to the runway surface and started the data recording devices. The test specimens were then abraded approximately 6 seconds at which time the hydraulic system automatically raised them from the runway surface and shut off the data recorders. The control circuit and all data recording devices operated off the on-board power generator of the ITTV.

Instrumentation.- The test apparatus was instrumented with a load cell located in the lower linkage arm (fig. 2). During abrasion test runs the friction force developed between the specimen and the runway surface produced a tensile force in the lower arm. The strain induced by this tensile force was converted by the load cell into an electrical signal which was amplified and filtered through a 2-Hz low-pass filter. The signal was then fed to a two-channel strip-chart recorder to provide a force data trace. This force measurement was used to calculate the friction and normal forces from a static analysis of the specimen holder given the applied load, the angle of inclination of the linkage arms, and the holder dimensions.

The test apparatus was also instrumented with a limit switch (fig. 2). The limit switch triggered an event marker on the strip-chart recorder when the test specimen was lowered to the runway surface at the start of the test. When the test was complete, the test specimen was raised, the limit switch was released, and the event marker returned to its original position. The test run time was then determined by counting the length of travel of the event marker and dividing that value by the chart speed.

In addition, temperature measurements were monitored by a thermal scanner during each abrasion test from three iron-constantan type J thermocouples. Two of the thermocouples were attached to the I-beam test specimen, one on the I-beam web and one on the backside of the lower flange which was adjacent to the runway surface, and the third measured ambient temperature. Temperature readings were output from a printer every two seconds during the abrasion test. The strip-chart recorder, filter, amplifier, thermal scanner and printer were mounted to the test trailer as shown in figure 2.

Procedure

Prior to testing, all pertinent data such as test specimen dimensions and mass and test parameters such as load and velocity were recorded. The weight necessary to achieve the desired test pressure was attached to the specimen holder. The test operator activated the control circuit to begin the test from a remote switch inside the ITTV cab, once the test velocity had been achieved. The driver of the ITTV maintained this speed for approximately 15 seconds to ensure constant velocity during the entire run time of the test. Following the test, the test specimen mass was recorded and the force data trace and thermal printout removed and labeled. This procedure was repeated for each test.

Specimens

Figure 3 shows one aluminum and one graphite-epoxy I-beam stiffened skin test specimen and their typical dimensions. The composite specimens were all fabricated with a front ski as shown in figure 3. The purpose of the ski was to help smooth the initial contact of the specimen to the runway surface. The aluminum specimens were also outfitted with front skis as well. Twenty specimens (5 each of four different material types) were fabricated. Table I shows the skin materials and, in the case of the composite materials, the ply lay-up. The graphite-epoxy skins were made from AS4/3502 material and contained 20 plies (symmetric lay-up). The two hybrids were constructed of the same material and lay-up except that the 90 degree plies were replaced by S-2 Glass/3502 for the hybrid 1 and by alternating strips of AS4/3502 and S-2 Glass/3502 for the hybrid 2.

Parameters

Pressure conditions.— The effect of pressure on specimen wear behavior and coefficient of friction was determined for each material at pressures of 2.0, 3.2, and 5.0 psi. Typical loading conditions on the skin panels of a transport airplane during an emergency belly landing would fall in the range of 2.0 to 5.0 psi. These test pressures were achieved by placing lead

weights on the specimen holder above the test specimen. All tests to determine the effect of load on friction and wear behavior were performed at a test velocity of 32.5 mph.

Velocity range.— Typical touchdown velocities of transport airplanes are approximately 140 to 160 mph. This high velocity range was unattainable with the ITTV and trailer system. However, a range of velocities was chosen for testing purposes. Tests at 16.0, 32.5, 45.0 were performed on each test material at a pressure of 3.2 psi, such that velocity was the only test variable.

RESULTS AND DISCUSSION

The general appearance of the abraded surface is shown in figure 4 for a typical aluminum, graphite-epoxy, hybrid 1, and hybrid 2 test specimen. The wear surface of the aluminum specimens contained rough, jagged grooves which were regularly spaced along the direction of sliding. The three composite specimens exhibited a wear surface with long grooves similar to the aluminum specimen, although the composite surfaces were smoother and the grooves were not quite as deep. The two hybrid specimens, shown on the right side of figure 4, contained patches where the glass layers abraded. These patches are the light areas seen on the surfaces.

In the following sections, the effects of independently varying the pressure and velocity on the wear behavior of the four different specimen types are discussed and comparisons are made between materials. In particular, the discussions will center on how the specimen wear rate and wear index are affected by the test variables. The wear rate is defined to be the reduction in specimen thickness per unit of run time and is calculated from the following equation:

$$\text{Wear rate} = \frac{m_i - m_f}{\rho l w (t_r)}$$

where

m_i	initial mass
m_f	final mass
ρ	density of skin material
l	specimen length
w	specimen width

t_r run time

Thus, wear rate was computed in dimensions of inches per second. An obvious means of nondimensionalizing the results is to divide the wear rate by the test velocity. This parameter is called the wear index and is computed from:

$$\text{Wear Index} = \frac{\text{Wear Rate}}{\text{Velocity}}$$

The wear index may be interpreted as an effective wear angle since it is the ratio of the downward wear velocity of the skin to the horizontal drag velocity. In addition to the variations in wear rate and index, comparisons between the four test materials are made based on the coefficient-of-friction data and on the temperature-time histories.

Wear Behavior

Effect of pressure.- The specimen wear rate as a function of normal pressure, shown in figure 5, exhibited a linear relationship for the four materials tested. The data from each test are given in Table II. A least-squares linear curve fit was made through the points. This technique gave a good fit to the data except for the hybrid 2 material, as can be seen in figure 5. The aluminum specimens exhibited the lowest overall wear rate of all the materials tested at every pressure level. The composite specimens had wear rates generally 2 to 3 times higher than the aluminum. Of the composites, the standard graphite-epoxy and hybrid 1 specimens showed a more dramatic increase in wear rate with an increase in load than did the hybrid 2 material.

Effect of velocity.- Results of the abrasion tests performed at velocities of 16, 32.5, and 45.0 mph are shown in figures 6 and 7 and the data are listed in Table II. A least-squares linear curve fit was used to obtain the lines through the data points. As in the wear rate vs. load plots, this technique worked well to describe the behavior of the aluminum, graphite-epoxy, and hybrid 1 tests, but not for the case of the hybrid 2 material.

Wear rate increased with velocity for the aluminum, graphite-epoxy, and hybrid 2 materials, as seen in figure 6. The data for the hybrid 1 material at the higher velocities also reflects this same trend. However, the wear rate for the hybrid 1 material at 16 mph is much higher than is typical of the other composite materials at that velocity. This data point was included in the least squares fit which consequently resulted in the downward gradient for the hybrid 1 curve. The high value of the wear rate for the hybrid 1 material at 16 mph cannot be explained from the test procedures. Figure 6 shows that aluminum has a wear rate 2 to 3 times lower than

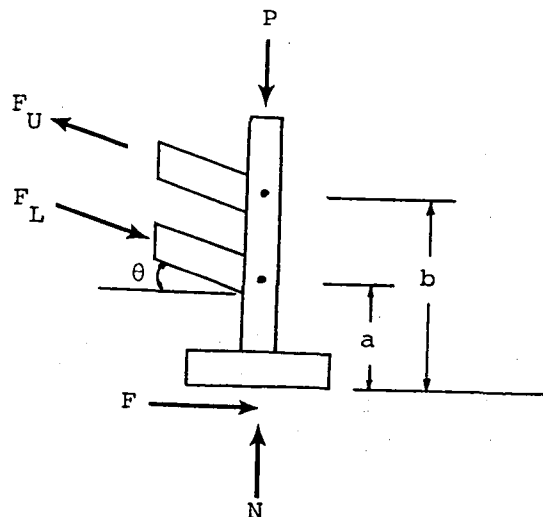
the composite materials tested for a given velocity. Also, the aluminum wear rate as a function of velocity has a much lower gradient than that of the composites. In general, the effect of varying the velocity is not as great as the effect of varying the pressure on the wear rate of the materials tested.

Figure 7 shows a plot of wear index, defined as the normalized wear rate, versus velocity. The data indicate that the wear index tends to decrease as the velocity increases for the materials tested. However, as in figure 6, the data point at 16 mph for the hybrid 1 material is much higher than the other composite data at that same velocity. This anomaly in the hybrid 1 data results in the extreme downward gradient for the wear index vs. velocity curve making it inconsistent with the majority of the composite data. The composite wear index is 2 to 3 times higher than the aluminum for a given test velocity, although the gradients appear to be approximately the same.

Coefficient-of-Friction Data

The frictional forces developed between the test specimen and the runway surface were calculated from a static analysis of the specimen holder (sketched below) given the applied load P , the angle of inclination of the linkage arms θ , and the force output measured from the load cell F_L .

Typical force traces from the load cell for the four test materials under identical test conditions are shown in figures 8, 9 and 10. The variations in the force plots are attributed to bouncing of the test apparatus as the I-beam test specimen abraded over expansion joints in the runway. These variations are negated by using the average force in the lower arm for calculating the coefficient-of-friction. This value was obtained by digitizing the force trace to find the area under the curve, then dividing by the test run time. The average value of the force is indicated by a straight line on each of the force traces.



The coefficient of friction μ is derived from the computed frictional force based on the average force as measured in the lower linkage arm. Sum of the moments yields,

$$F = F_L (\cos \theta) \left(\frac{a}{b} - 1 \right)$$

Sum of the forces in the horizontal and vertical directions yields,

$$N = P + F_L (\sin \theta) \left(1 - \frac{a}{b} \right)$$

Therefore, the coefficient of friction is given by

$$\mu = \frac{F}{N} = \frac{F_L (\cos \theta) \left(\frac{a}{b} - 1 \right)}{P + F_L (\sin \theta) \left(1 - \frac{a}{b} \right)}$$

Plots of the coefficient of friction as a function of pressure and velocity are shown in figures 11 and 12, respectively, and the data are listed in Table II. A least-squares linear curve fit was made through the points. This technique gave a reasonable fit to the data for each of the test materials.

The coefficient of friction increases with load for both the aluminum and composite specimens, as seen in figure 11. The aluminum has a coefficient of friction 1.5 to 2 times the value for the composite materials at every pressure level. This trend is seen also in figure 12 which shows a plot of coefficient of friction versus velocity. Results shown in figure 12 indicate that coefficient of friction remains fairly constant with increases in velocity. These data imply that under the conditions of an airplane belly landing, a transport with a graphite-epoxy composite skin could slide twice as far as a similar transport with an aluminium skin, and the consequent wear would be several times greater.

Temperature Data

Temperature variation during the abrading process was obtained from thermocouples attached to the I-beam test specimen. Table III lists the temperature recordings for each of the tests from the ambient thermocouple and from the thermocouple attached to the backside of the lower flange. Output from the thermocouples was printed every two seconds during a test run. Figure 13 is a plot of the temperature difference versus time for the four materials tested at 3.2 psi and 32.5 mph. The aluminum reached the highest temperature, approximately 15 degrees above ambient, and had the greatest rate of increase in temperature with time. The three composite materials did not exhibit any significant rise in temperature during the abrasion process. The trends seen in this test are typical of the temperature-time behavior in all of the abrasion tests.

CONCLUDING REMARKS

The objective of this investigation was to compare the friction and wear response of aluminum and composite materials when subjected to loading conditions similar to those experienced by the skin panels on the underside of a transport airplane during an emergency sliding landing on a runway surface. A test apparatus was developed to abrade I-beam stiffened skins on a runway surface under these conditions. Four types of materials (aluminum, standard graphite-epoxy, and two glass hybrid composites) were used to fabricate the skin specimens. The skins were abraded under a range of test pressures and velocities. In addition, thermocouples were attached to the I-beam test specimens to obtain the temperature-time history during abrasion.

Comparisons between the responses of the four test materials were made based on wear rate, wear index, coefficient-of-friction data, and temperature response. Major findings of this investigation include:

1. Wear rate for both the aluminum and the composite materials was a linear function of pressure and velocity.
2. Composite materials wear 2 to 3 times faster than aluminum under similar test conditions.
3. The coefficient of friction for the composite materials was approximately half that of the aluminum.
4. Aluminum exhibited a high rate of increase in temperature, while the composite materials showed little increase above ambient level during abrasion.

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1. Passengers Praise Pilot for Actions in Accident. Times-Herald (Newport News, Va.), 83rd year, no. 71, Mar. 24, 1983, p 13.
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TABLE I.- SKIN MATERIALS

Material	Lay-up
Aluminum: 7075-T76	
Composite: Gr-Ep AS4/3502 Hybrid 1 AS4/3502 with S-2 Glass for 90 degree plies Hybrid 2 AS4/3502 with S-2 Glass and AS4 alternating strips for 90 degree plies	 (135,45,135,90,45,0,135,90,45,0) _s

TABLE II.- Test Conditions and Results

Test No.	Material Type	Test Pressure (psi)	Test Velocity (mph)	Wear Rate (in/sec) $\times 10^{-3}$	Wear Index (in/in) $\times 10^{-6}$	Coefficient of Friction
1	Aluminum	2.0	32.5	0.50	0.86	No Data
2	"	3.2	16.0	0.57	2.03	0.18
3	"	3.2	32.5	0.92	1.60	0.19
4	"	3.2	45.0	0.93	1.18	0.23
5	"	5.0	32.5	1.76	3.07	0.24
6	Gr-Ep	2.0	32.5	1.08	1.88	0.06
7	"	3.2	16.0	1.57	5.55	0.15
8	"	3.2	32.5	1.79	3.13	0.10
9	"	3.2	45.0	2.95	3.72	0.14
10	"	5.0	32.5	3.76	6.55	0.15
11	Hybrid 1	2.0	32.5	1.28	2.23	0.10
12	"	3.2	16.0	2.73	9.69	0.10
13	"	3.2	32.5	1.91	3.33	0.10
14	"	3.2	45.0	2.12	2.67	0.11
15	"	5.0	32.5	3.85	6.71	0.19
16	Hybrid 2	2.0	32.5	1.57	2.73	0.08
17	"	3.2	16.0	1.08	3.84	0.09
18	"	3.2	32.5	0.91	1.59	0.13
19	"	3.2	45.0	2.51	3.16	0.08
20	"	4.1	32.5	2.36	4.12	0.17

TABLE III.- Temperature Data

Test No.	Material	Temperature Readings (deg. F)				
		Ambient	2 sec	4 sec	6 sec	8 sec
1	Aluminum	81.7	81.8	81.9	No Data	82.7
2	"	66.8	67.7	No Data	68.6	69.5
3	"	66.5	68.9	72.4	75.8	79.5
4	"	73.9	73.5	79.6	88.3	No Data
5	"	71.0	71.3	72.0	77.7	82.3
6	Gr-Ep	81.6	83.6	84.5	84.2	84.2
7	"	67.6	68.8	68.9	69.1	69.2
8	"	70.0	70.0	70.0	70.2	No Data
9	"	75.8	76.6	76.8	77.4	No Data
10	"	71.8	71.8	71.9	No Data	No Data
11	Hybrid 1	83.3	82.9	83.0	83.0	83.2
12	"	77.5	78.9	78.9	79.4	79.5
13	"	77.7	77.7	77.9	78.2	No Data
14	"	77.7	76.5	77.1	77.7	77.7
15	"	71.8	71.7	71.8	71.8	72.0
16	Hybrid 2	79.5	84.7	84.7	84.7	84.7
17	"	80.4	77.3	No Data	78.5	No Data
18	"	79.3	79.6	No Data	No Data	80.3
19	"	77.8	78.4	78.4	78.7	79.2
20	"	73.1	72.1	72.2	72.4	72.4

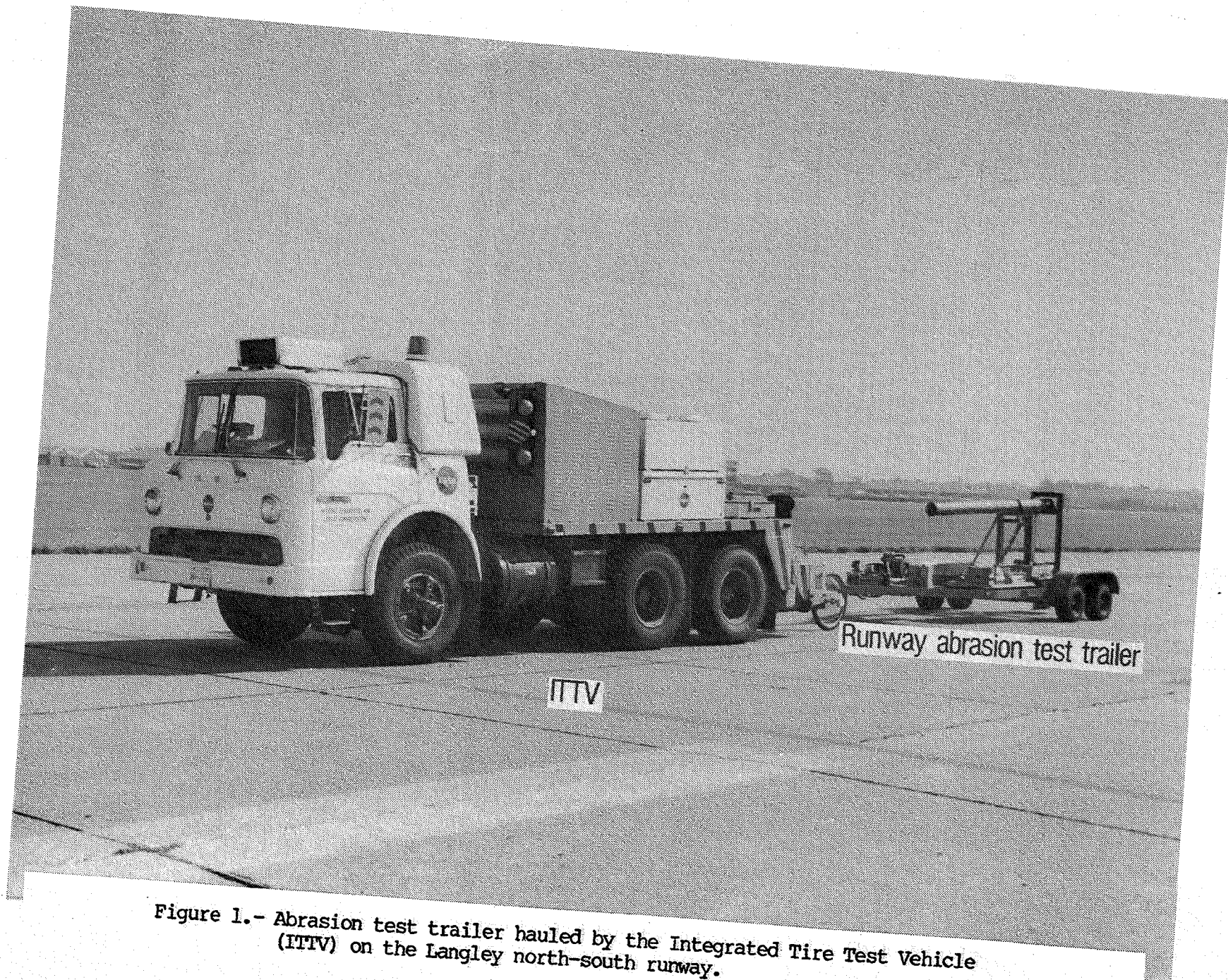


Figure 1.- Abrasion test trailer hauled by the Integrated Tire Test Vehicle (ITTV) on the Langley north-south runway.

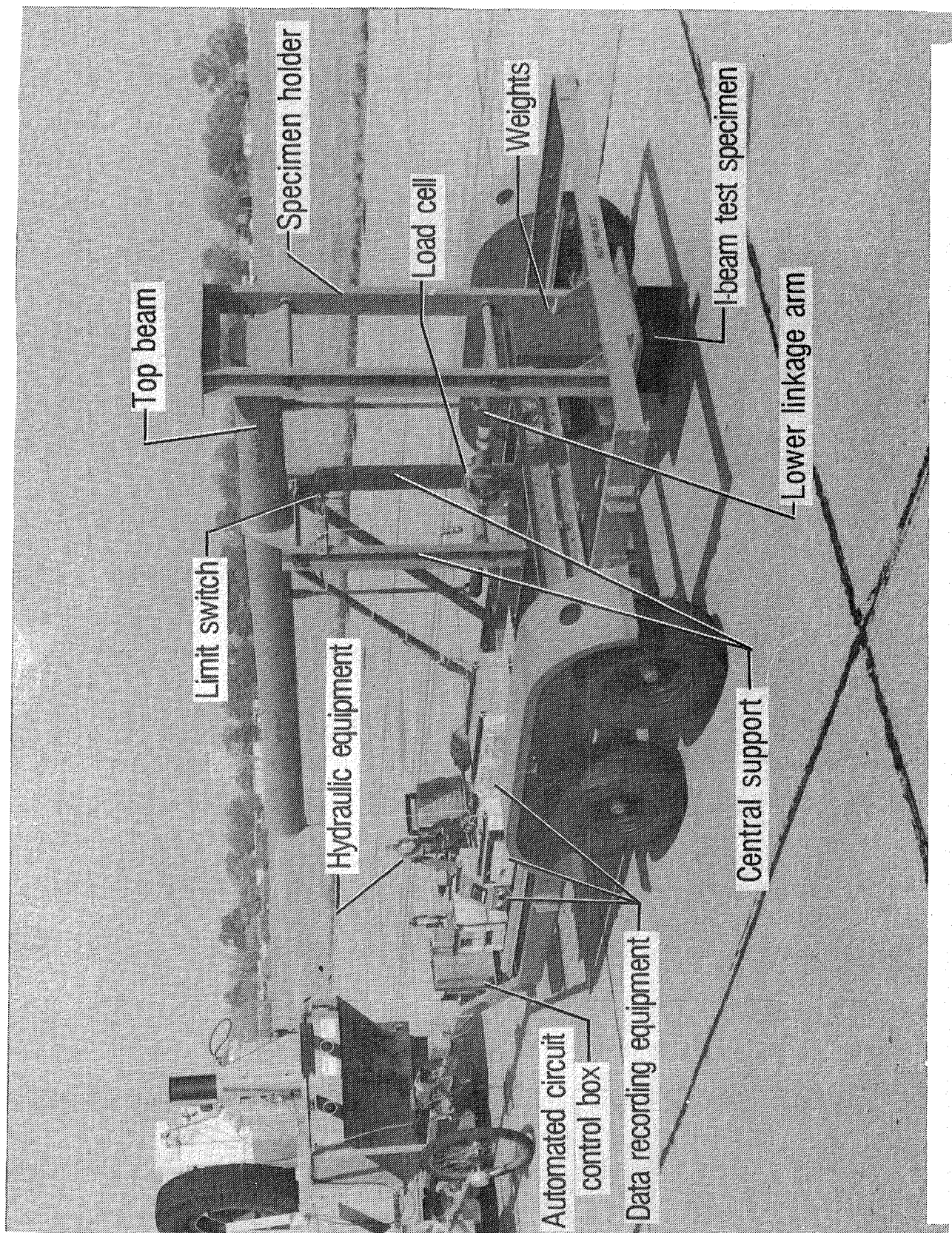


Figure 2.- Abrasion test trailer and apparatus.

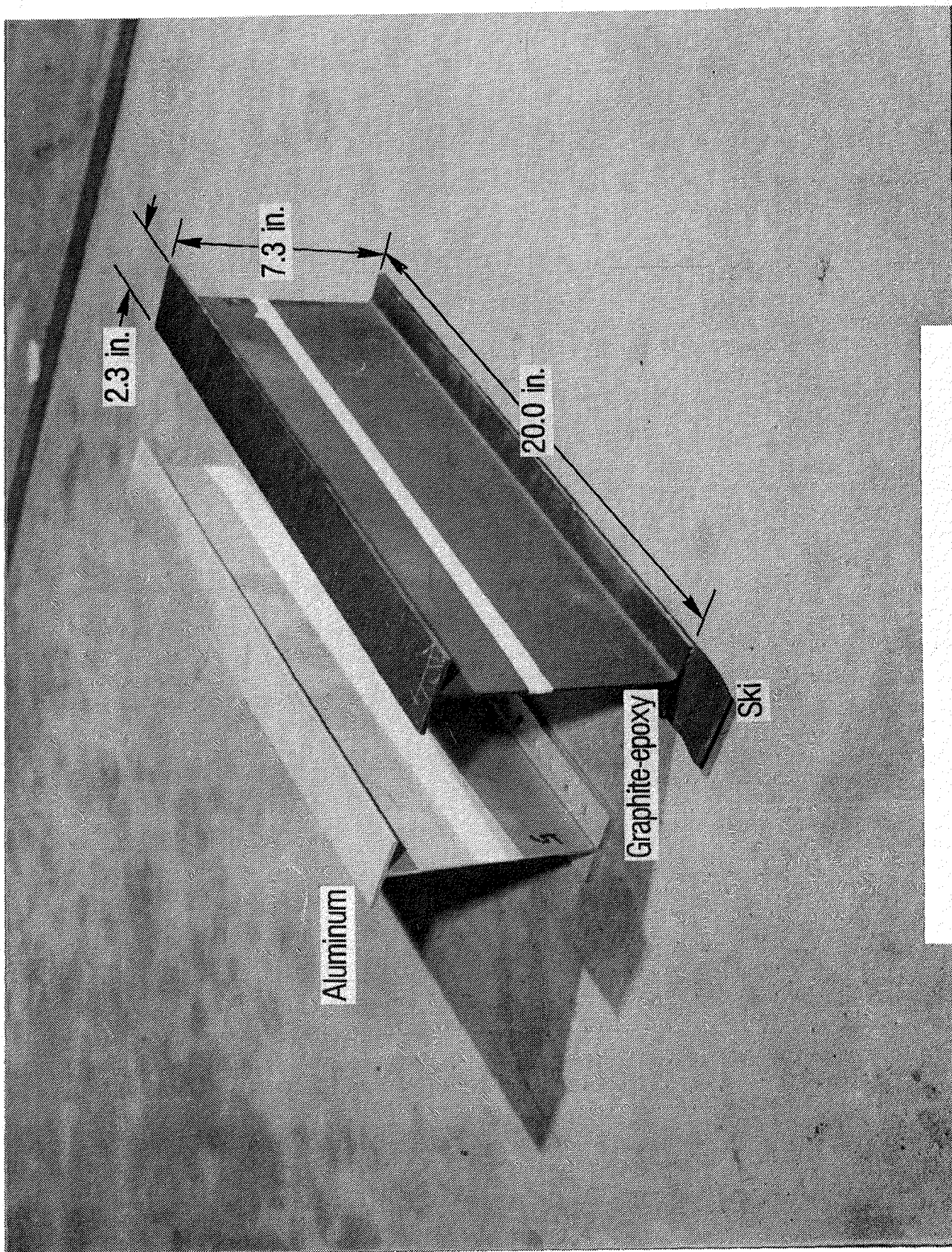


Figure 3.- I-beam stiffened skin test specimens.

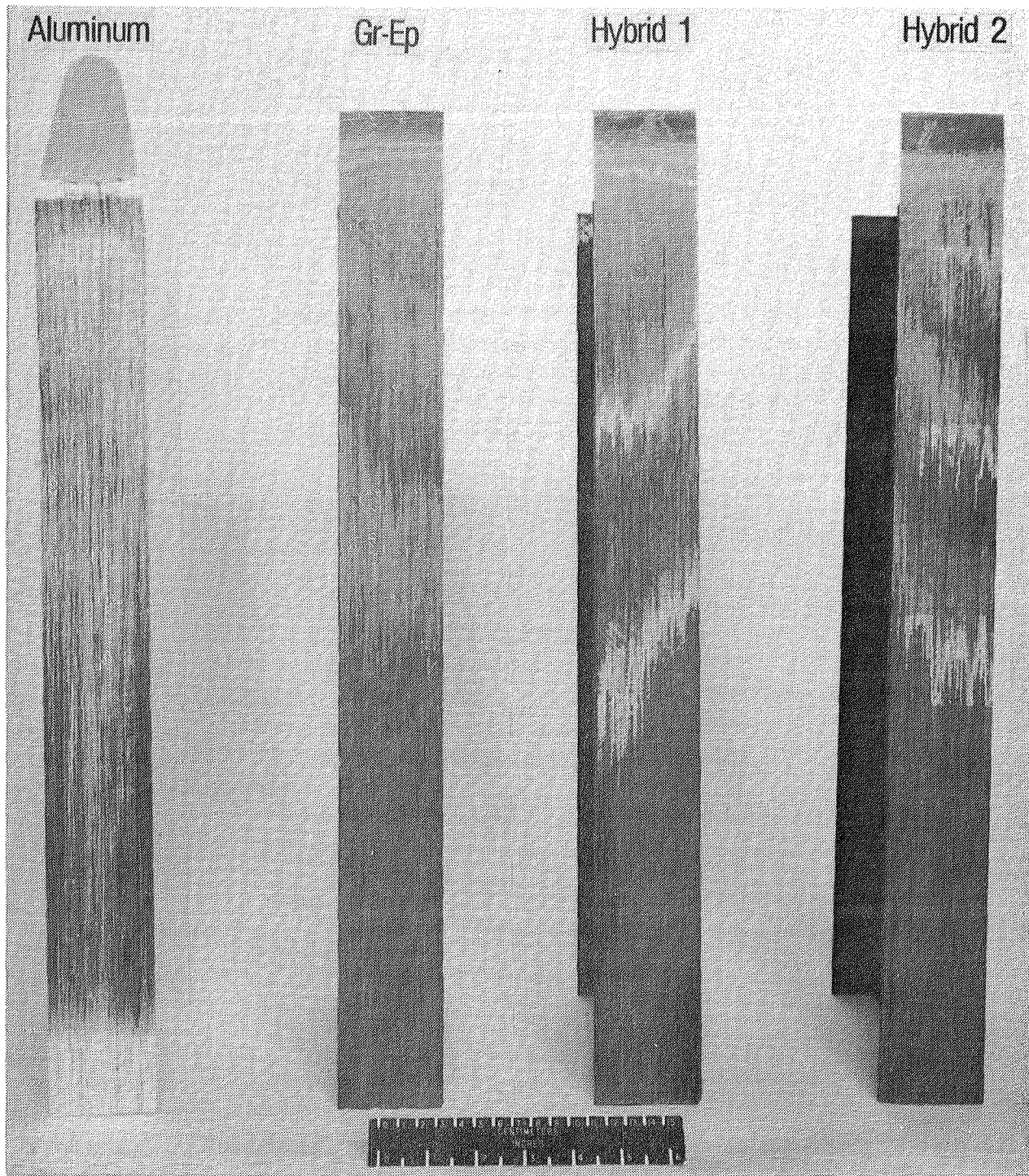


Figure 4.- Typical abraded surfaces of four test specimens.

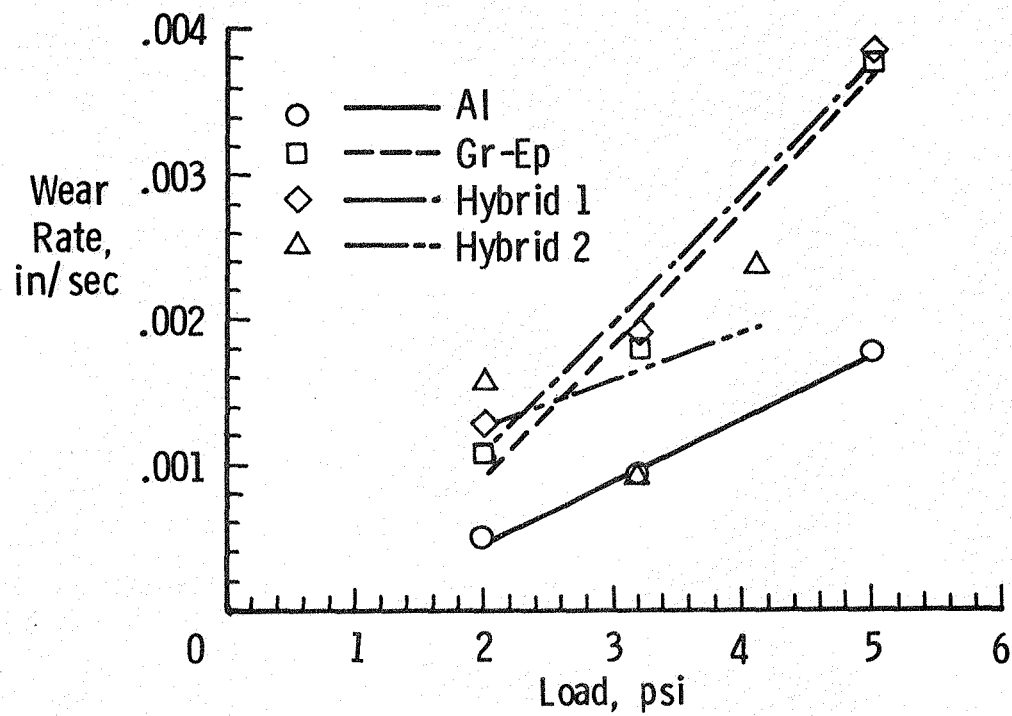


Figure 5.- Wear rate as a function of normal loading for a test velocity of 32.5 mph.

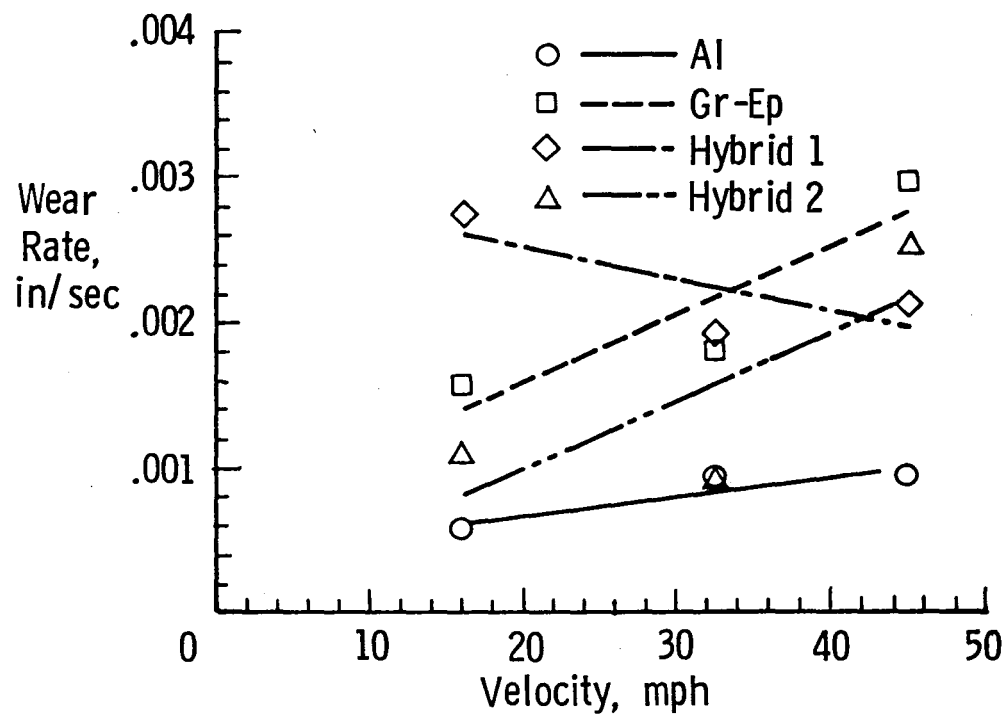


Figure 6.- Wear rate as a function of velocity for a test pressure of 3.2 psi.

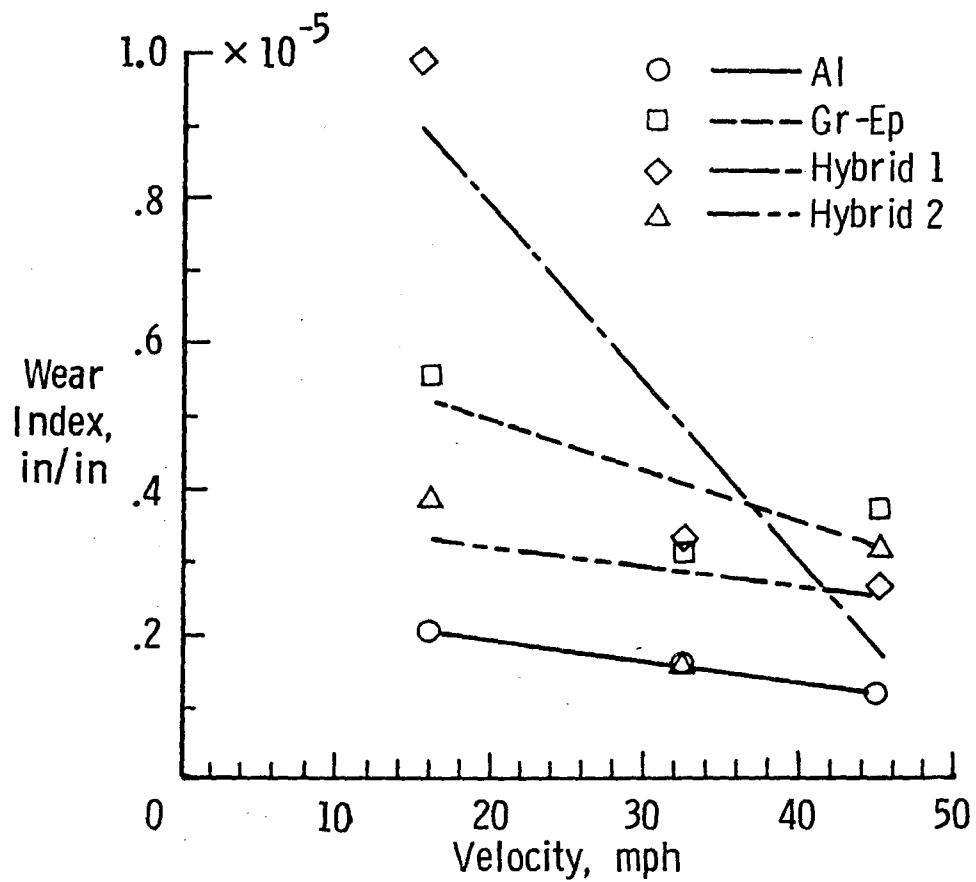


Figure 7.- Wear index as a function of velocity for a test pressure of 3.2 psi.

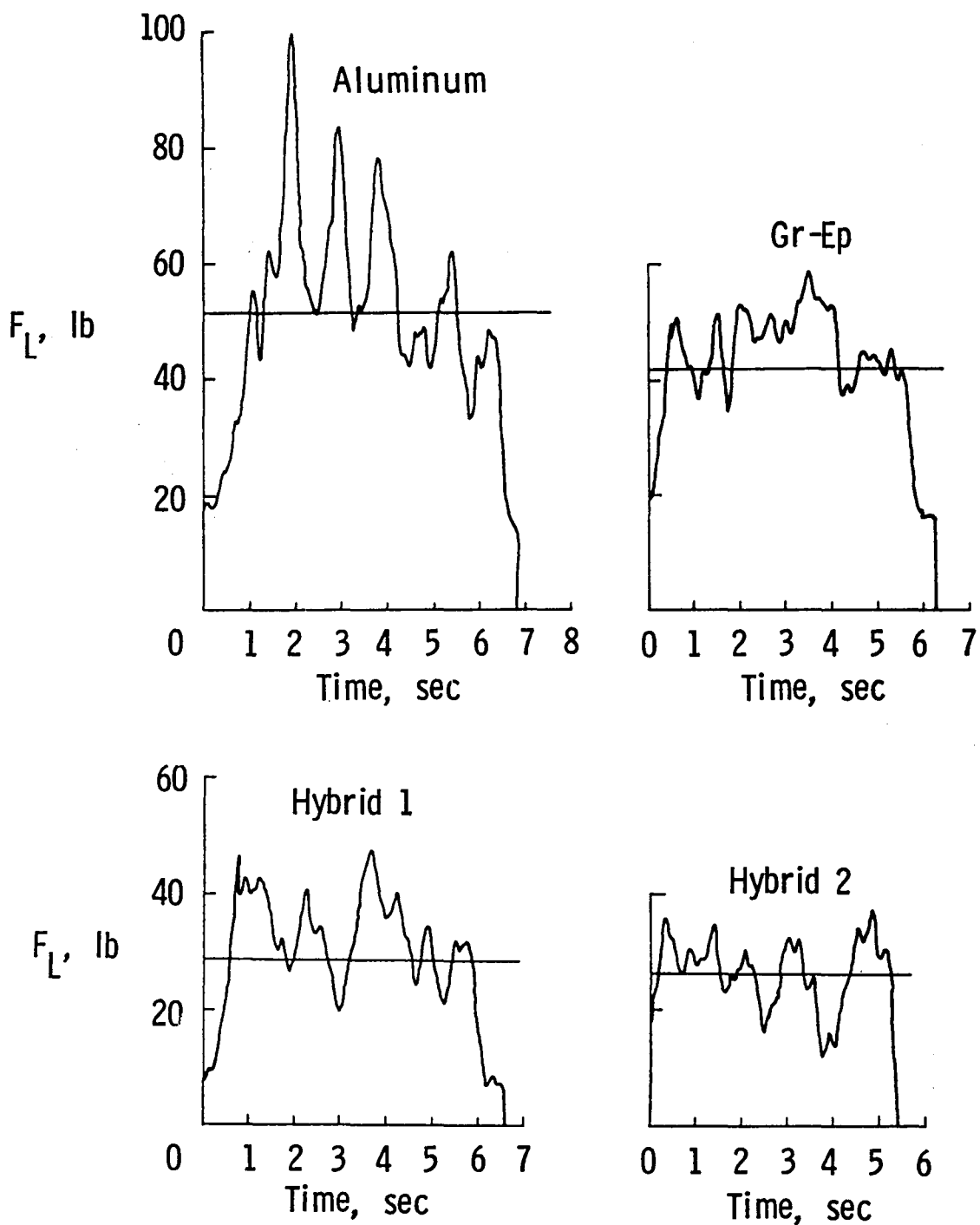


Figure 8.- Force traces output from the load cell for tests at 3.2 psi and 16 mph. Horizontal line represents the value of the average force.

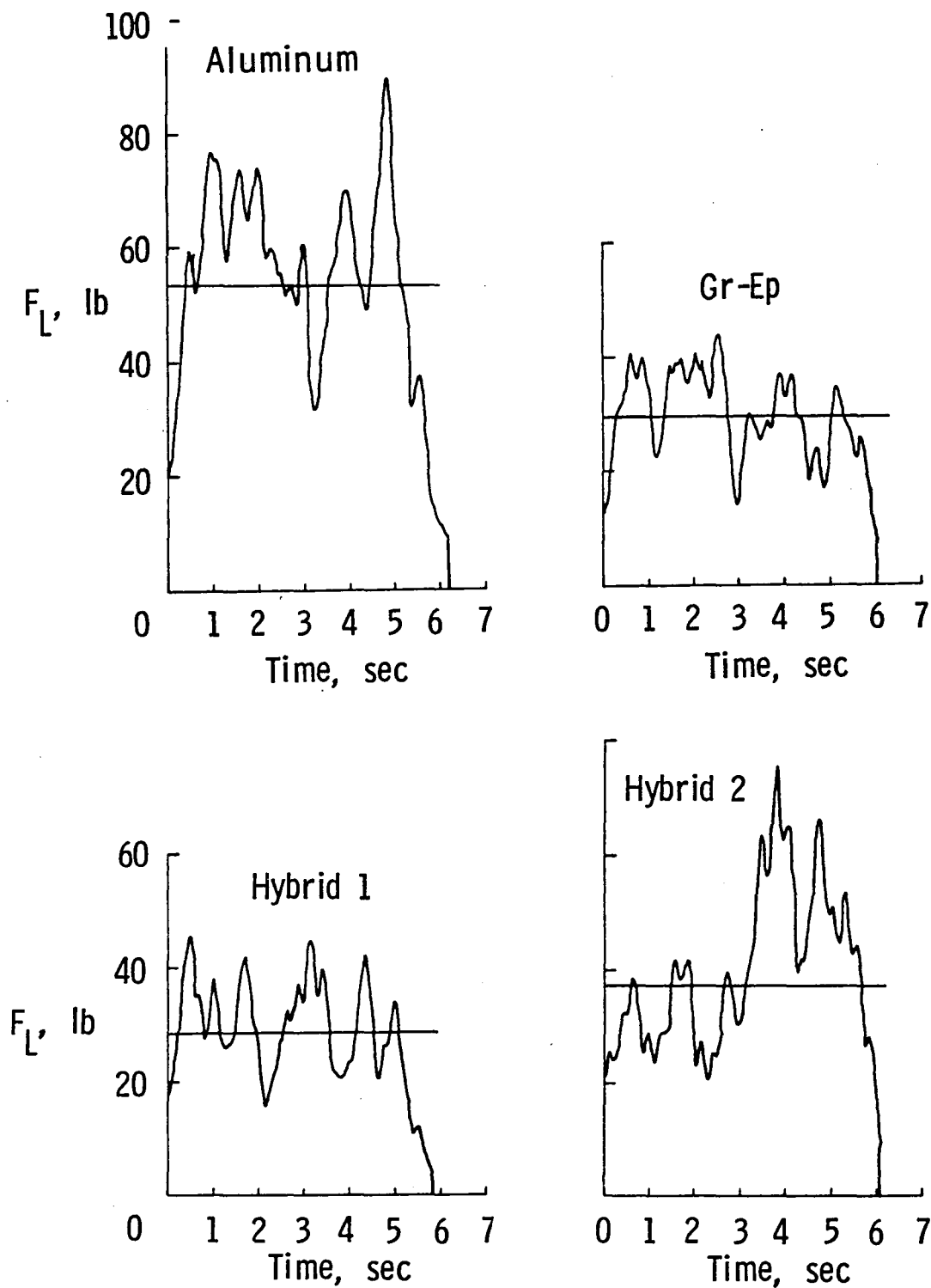


Figure 9.- Force traces output from the load cell for tests at 3.2 psi and 32.5 mph. Horizontal line represents the value of the average force.

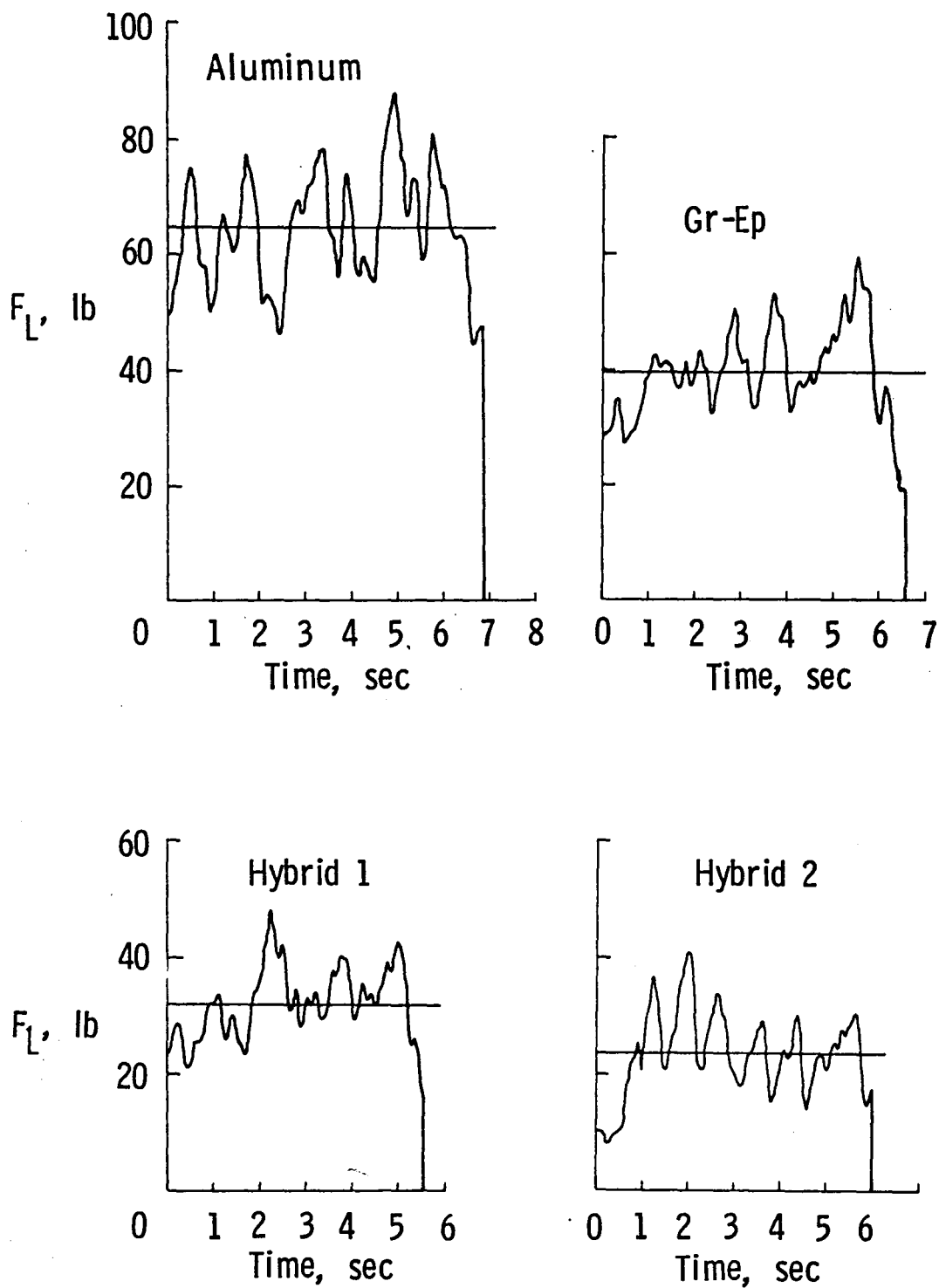


Figure 10.- Force traces output from the load cell for tests at 3.2 psi and 45 mph. Horizontal line represents the value of the average force.

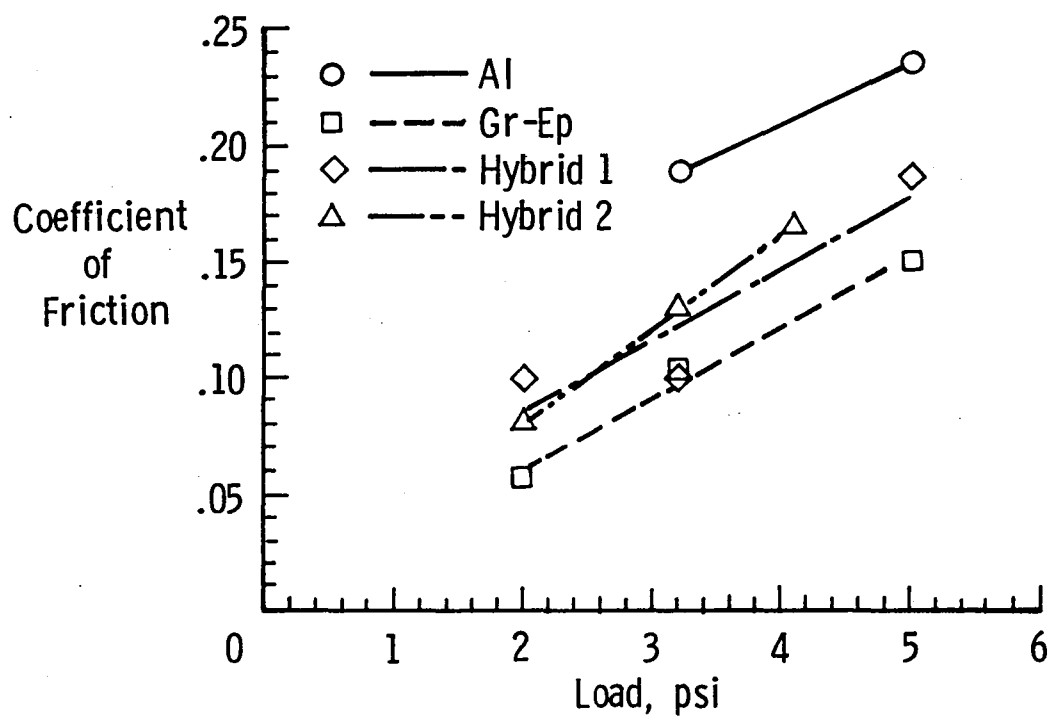


Figure 11.- Coefficient of friction as a function of normal loading.

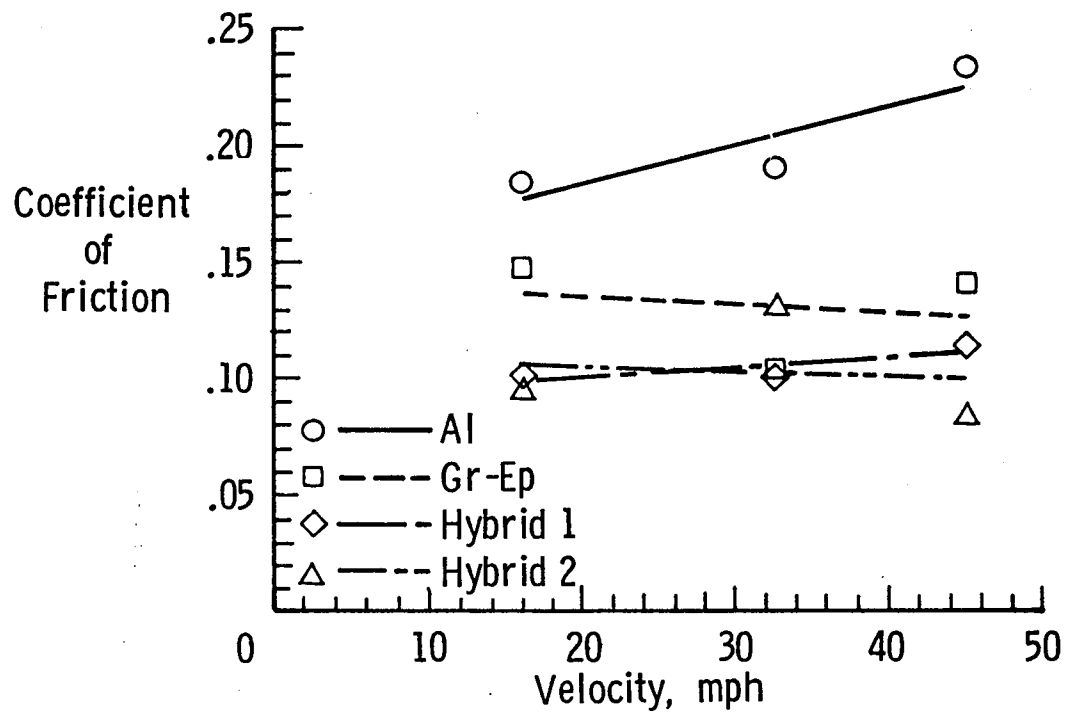


Figure 12.- Coefficient of friction as a function of velocity.

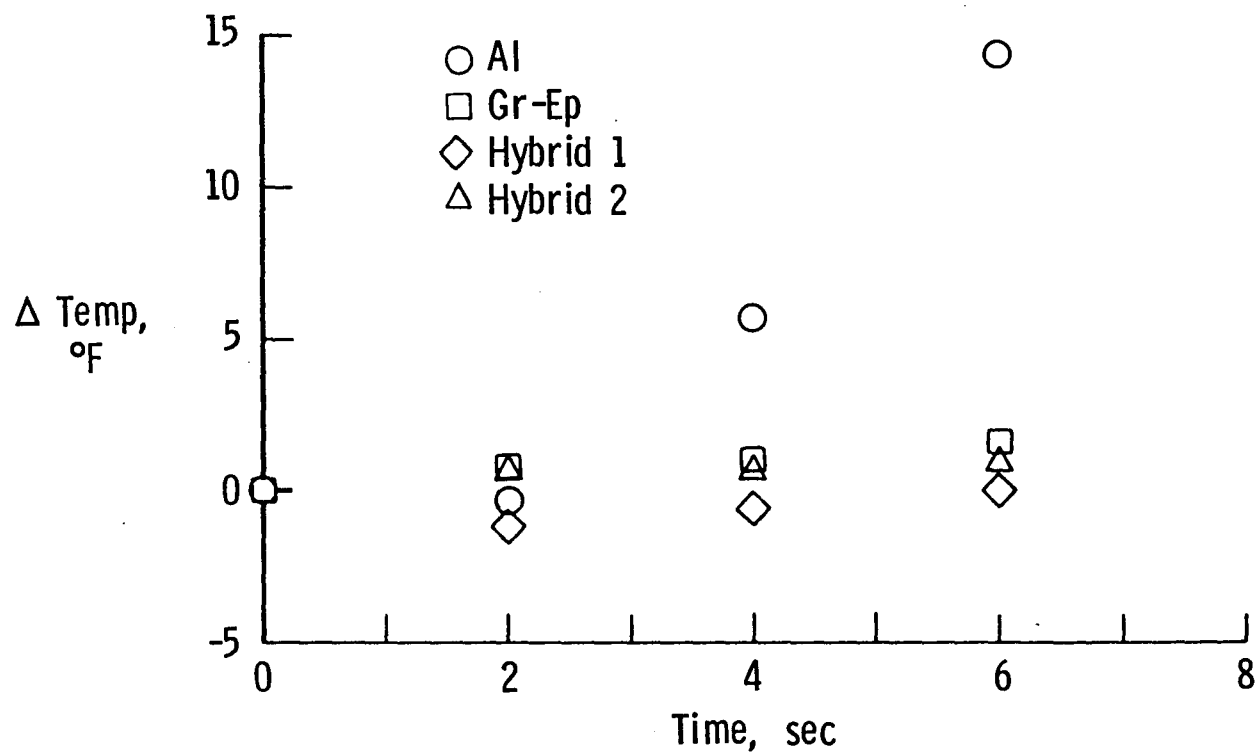


Figure 13.- Temperature difference versus time for the tests at 3.2 psi and 32.5 mph.

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16. Abstract Friction and wear behavior was determined for I-beam stiffened skins constructed of aluminum, graphite-epoxy composite, and glass hybrid composite under abrasive loading conditions typical of those occurring on the underside of a transport airplane during an emergency belly landing. A test apparatus was developed to abrade the test specimens on actual runway surface under a range of pressures (2-5 psi) and velocities (16-50 mph). These parameters were chosen to fall within the range of conditions typical of an airframe sliding on a runway surface. The effects of the test variables on the wear rate and the coefficient of friction are discussed and comparisons are made between the composite materials and aluminum. In addition, the test apparatus was equipped to monitor the temperature variations on the backside of the skins during abrasion and these results are presented.					
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